CHAPTER – 5

SUMMARY AND CONCLUSIONS

5.1 Background

In the last two decades, researchers worldwide have sought suitable reinforcements to address the challenges of steel-based reinforcements, such as corrosion, durability, specific gravity, concrete cover, and contour ability. Continuous textile structures have emerged as promising alternatives, leading to ongoing efforts to develop suitable materials. High-performance fibres such as carbon, AR glass, and basalt have gained significant interest in the composite industry due to their superior mechanical properties and non-corrosive nature, making them ideal for infrastructure applications in the form of fibre-reinforced plastics (FRPs) and textile-reinforced concrete (TRC).

However, these high-performance fibres exhibit low ductility, necessitating yarn or fabric hybridization to improve ductility. Thermoplastic fibres such as PP and PET have the potential to enhance cement composite properties and improve yarn-matrix bonding. Previous research confirms the advantages of hybrid yarn and fabric structures in concrete regarding cost and mechanical properties, though limited research exists in this area [28]–[32], [34], [35]. Modifications in yarn structure, such as twist and crimped geometry, also positively affect the pull-out behaviour (fibre-concrete bond) of TRC[12], [25].

In this research, hybrid yarns were developed to combine the high tensile strength of high-performance fibres with the ductile behaviour of thermoplastic fibres. High-performance filament bundles have smooth surfaces with thousands of multifilament, making cementitious matrix penetration inside the bundle challenging, resulting in poor bonding between the filaments and the mortar matrix. This study incorporated helically wrapped twisted and braided PET yarns secured by epoxy resin to improve fibre-mortar matrix bond behaviour through mechanical anchorage.

This research also aimed to investigate the mechanical performance of mortar in terms of yarn pull-out, tensile, and flexural behaviour, reinforced with three popular high-performance filaments (AR glass, basalt, and carbon) with similar yarn tex and fabric geometry. Additionally, a small weight fraction (0.25%) of PP fibres was used in the mortar mix to leverage the benefits of fibres alongside fabric reinforcement. The current research focused on investigating the impact of hybrid (core-sheath) yarn structure on the mechanical properties of Textile-Reinforced Concrete (TRC).

5.2Cross-section micrograph of yarn specimens

The parent roving bundle, composed of smooth multifilament strands, has poor inter-filament cohesion, leading to filament spreading and a flattened cross-section. The shape factor is highest for carbon (1.80), followed by basalt (1.74) and AR glass (1.31). Epoxy coating reduces spreading, making the cross-section more oval or elliptical. In hybrid yarn structures, the PP sheath and PET wrapping provide a binding effect, preventing filament dispersion and resulting in a more circular cross-section. Epoxy coating and hybridization further reduce the shape factor, improving filament-mortar interfacial contact, which enhances bonding and influences bond stress.

5.3 Tensile behaviour of yarn and fabric specimens

When comparing the tensile behaviour of parent AR glass, basalt, and carbon yarns (with filament bundle strands of nearly equivalent tex), carbon shows the highest peak load, followed by basalt, and AR glass has the lowest, reflecting their inherent mechanical properties. Similar trend is observed for hybrid yarns and fabric specimens.

Yarn hybridization and epoxy coating significantly enhance the tensile performance of ARG, basalt, and carbon yarns. In DREF spun yarn, the PP fibre sheath binds the high-performance multifilament core, further reinforced by thermal treatment and PET helical wrapping. The epoxy coating increases stiffness, allowing the yarn to behave like a monofilament, thereby improving fibre activation, load transfer, and load-sharing. The high-performance roving core bears the load, while the low-modulus PP and PET fibres enhance ductility. This synergy increases peak load capacity while improving elongation, displacement, strength, and ductile behaviour.

5.4 Cylinder split tensile behaviour of Mortar cyclinder

As compared to the mean split tensile strength for the unreinforced cylinder the basalt thermoplastic fabric composite reinforced cylinder exhibited an improvement of 12%. This suggests that incorporating fabric reinforcement in mortar cylinder specimens enhances resistance to splitting under compressive load.

5.5 Yarn pull-out behaviour of YRCM specimens

The yarn pull-out test for parent (uncoated)AR glass, basalt, and carbon YRCM specimensas well as their hybrid structures based YRCM shows highest pull-out load for carbon, followed by basalt and AR glass.

AR glass yarn specimens exhibit the highest bond stress values among both uncoated and hybrid YRCM specimens, followed by carbon, and the lowest for basalt. For energy absorption, uncoated yarn-reinforced mortar specimens show the highest values for AR glass, followed by basalt, and the lowest for carbon. In contrast, hybrid YRCM specimens have the highest energy absorption for basalt yarn, followed by carbon, and the lowest for AR glass.

Uncoated parent yarns, being flattened and less consolidated, have a larger contact perimeter with the mortar, resulting in lower bond stress. In contrast, epoxy-coated and hybrid yarns, with more compact cross-sections, exhibit better structural integrity due to resin impregnation and the binding effect of PP and PET fibres. The hybrid yarn's surface-twisted PET and epoxy coating enhance mechanical anchorage, increasing peak pull-out load and bond stress. This structure improves fibre activation, load transfer, and load-sharing, ensuring stronger mechanical anchorage within the cementitious matrix.

5.6 Yarn pull-out behaviour of FRCM specimens

The yarn pull-out test for parent (uncoated) AR glass, basalt, and carbon FRCM specimens, as well as their hybrid structures based FRCM, shows the highest pull-out load for carbon, followed by basalt, with the lowest for ARG.

Comparing the peak pull-out load, bond stress, and energy absorption, hybrid carbon yarn outperforms hybrid ARG and basalt yarns. Similarly, uncoated carbon yarn performs better than uncoated ARG and basalt yarns. Fibre pull-out incidents are more prevalent in carbon FRCM specimens, is attributed to the greater number of carbon filaments participating in the load-sharing process, the effective bonding between carbon filaments due to epoxy coating, and the larger surface perimeter contact of the carbon bundle with the concrete (9.12 mm for hybrid carbon yarn, 7.22 mm for hybrid basalt yarn, and 4.82 mm for hybrid ARG yarn, as shown in Table 4.4).

FRCM specimens show improved pull-out behaviour compared to YRCM specimens. This improvement is attributed to the combined effect of surface roughness from the helically wrapped twisted and braided PET yarns, epoxy coating, and the contribution of the woven fabric structure-specifically, the weft yarns-which introduce undulations that enhance bonding with the mortar matrix. In YRCM specimens, the primary contributors to the pull-out load are the increased surface roughness from the PET yarn wrapping and epoxy coating, which enhance bond performance.

Unlike basalt and carbon hybrid yarn specimens, the AR glass hybrid yarn specimen exhibited telescopic failure under pull-out loading. This failure mode suggests that epoxy resin penetration through the PP sheath was inadequate in the hybrid ARG yarn. Additionally, the zirconium coating on the AR glass bundle hindered effective bonding between the filaments and the resin, resulting in poor wetting of the AR glass filaments. Consequently, the inner core filaments slipped out, leaving the outer sleeve embedded in the mortar during the pull-out test. As a result, no significant crack development, damage, or spalling was observed in the concrete specimen during the yarn pull-out test of AR glass yarn and fabric specimens.

5.7 Uniaxial tensile behaviour of FRCM specimens

5.7.1 Comparison of tensile behaviour of parent, epoxy coated and hybrid yarn-based AR glass, basalt and carbon FRCM specimens

Regardless of fibre type, all FRCM specimens exhibit deflection-hardening (strain-hardening) behaviour. After matrix cracking, they sustain increasing load with the formation of fine multiple cracks, preventing sudden localized failure. The tensile load transfers to the fabric, which bears the applied forces during testing. This behaviour ensures progressive stress redistribution, multiple crack formations, and enhanced load-bearing capacity, ultimately improving ductility and energy absorption.

Carbon FRCM specimens have offered the highest tensile strength and energy absorption, followed by basalt and AR glass. Hybrid yarn-based FRCM specimens exhibit higher tensile strength and energy absorption than their parent counterparts, regardless of fibre type. This tensile behaviour of FRCM specimens is consistent with the tensile properties observed in the fabric tensile test results.

Replacing the parent (uncoated) fabric with epoxy-coated or hybrid yarn-based fabric increases the average number of cracks and reduces crack spacing in failed FRCM specimens, regardless of the fibre type. This indicates more uniform load transfer from the fabric to the mortar matrix in FRCM specimens. The occurrence of fine cracks and multiple cracking under tensile load is beneficial for FRCM specimens, particularly in hybrid yarn-based specimens, as it helps prevent sudden localized catastrophic failure.

5.7.2 Comparison of tensile behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric reinforced FRCM specimens

When comparing the tensile load versus displacement behaviour of different basalt yarn-based FRCM specimens – parent (uncoated), epoxy-coated TS fabric composite, and hybrid yarn-based TP fabric composite – the epoxy-coated basalt-based TS fabric composite exhibited the highest average tensile load, followed by the basalt hybrid yarn-based TP fabric composite, with the parent (uncoated) basalt having the lowest. Reinforcing basalt with TP fabrics in FRCM specimens improves the tensile load and tensile strength by 11.29%, while reinforcing with TS fabrics improves these properties by 21.86%, compared to the parent basalt fabric.

Similarly, energy absorption improves 31.46% with the hybrid yarn-based TP fabric composite and by 47.44% with the epoxy-coated TS fabric composite. The resin coating and impregnation within the basalt filament bundle enhance its load-bearing and load-sharing capabilities, enabling the fabric to sustain higher tensile loads in FRCM specimens. Post-tensile test images suggest that, replacing the parent basalt fabric with epoxy-coated TS and hybrid yarn-based TP fabric composites in mortar/concrete reinforcement resulted in an increase in fine microcracks, improved crack distribution, and reduced crack spacing. This indicates enhanced load transfer and stress redistribution, effectively preventing catastrophic (localized) failure.

5.7.3 Effect of number of layer reinforcement on tensile behaviour of FRCM specimens

When comparing the tensile load versus displacement behaviour of PP fibre-reinforced mortar (PP-FRC, control specimen) without fabric reinforcement to ARG and basalt epoxy-coated FRCM specimens with one and two layers of fabric, significant improvements were observed. Compared to the PP fibre-reinforced mortar specimen, FRCM specimens with one layer of ARG and basalt epoxy-coated fabric showed an improvement in tensile peak load by

250% and 433%, respectively. With two layers, the improvement was 740% and 1092%, respectively.

In terms of energy absorption capacity, as compared to the PP fibre-reinforced specimen, notable enhancements were seen with one layer of AR glass and basalt epoxy-coated fabric by 470% and 1485%, respectively. With two layers, the improvement was 2292% and 7234%, respectively.As the number of layers in FRCM specimens increases from one to two, the reinforcement ratio (fibre volume fraction) also increases, enhancing the tensile load-bearing capacity of TRC specimens. This improvement allows them to resist higher tensile forces before failure. Additionally, the increased number of fabric layers contributes to better deflection-hardening behaviour, improved ductility (displacement), and greater energy absorption, making the specimens more resilient under tensile loading. Reinforcing FRCM with continuous fabrics significantly enhances its tensile properties. High-performance fibres combined with PP fibres added as secondary reinforcement in mortar mixing synergistically improve load-bearing capacity, energy absorption, and ductility.

The images of failed specimens indicate that the PP-FRC specimen (without fabric reinforcement) exhibited tensile failure with two cracks, one leading to complete failure. In contrast, all AR glass and basalt FRCM specimens showed failure through a combination of fibre fracture (fabric rupture) and fibre pull-out, with multiple fine cracks running along the width of the specimen. The images also reveal an increase in the number of cracks and reduced crack spacing as the number of fabric layers increases from one to two layers, regardless of the fibre type (AR glass or basalt).

5.7.4 Effect of mesh size opening of fabric on tensile behaviour of FRCM specimens

The tensile load versus displacement behaviour of basalt hybrid yarn-based TP fabric composite reinforced FRCM specimens with varying mesh opening sizes (6 mm x 7 mm and 10 mm x 12 mm) shows that as the mesh opening size decreases from 10 mm x 12 mm to 6 mm x 7 mm, the average tensile peak load improves by 20%.

Similarly, there is a notable increase in tensile strength by 20.2% and energy absorption by 43.25% when the mesh size reduces from 10 mm x 12 mm to 6 mm x 7 mm. This improvement is attributed to the increased number of warp and weft yarns in the fabric, while maintaining the same dimensions of the FRCM specimen. Specifically, the fabric with a 10 mm x 12 mm mesh had four load-bearing warp yarns, whereas the 6 mm x 7 mm mesh had six.

The failure of both specimens following the tensile test suggests FRCM specimen failure through a combination of fibre fracture (fabric rupture) and fibre pull-out, with multiple fine cracks running along the width of the specimen. The images highlight a slight increase in the number of cracks and a decrease in crack spacing as the fabric mesh opening size decreases from 10 mm x 12 mm to 6 mm x 7 mm.

5.8 Flexural behaviour of FRCM specimens

5.8.1 Comparison of flexural behaviour of parent, epoxy coated and hybrid yarn-based AR glass, basalt and carbon FRCM specimens

The flexural test results of parent (uncoated) AR glass, basalt, and carbon FRCM specimens, as well as their hybrid structures, show the highest flexural peak load, flexural strength, and energy absorption for carbon, followed by basalt, with AR glass having the least. Hybrid yarn-based FRCM specimens display enhanced flexural strength and energy absorption compared to their parent counterparts across fibre types (AR glass, basalt, and carbon). This flexural behaviour aligns with the tensile properties observed in fabric tensile tests and the tensile behaviour of FRCM specimens. Failed FRCM specimens after flexural tests indicate an increase in fine microcracks and improved crack distribution from parent carbon fabric to epoxy-coated and hybrid yarn-based fabric. Hybrid yarns fail through a combination of fibre fracture and fibre pull-out, with warp yarns bridging to prevent catastrophic failure (complete separation) of the FRCM plate specimen.

5.8.2 Comparison of flexural behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric reinforced FRCM specimens

The flexural behaviour of parent basalt fabric, hybrid yarn-based basalt TP and TS fabric-reinforced FRCM specimens suggests that reinforcing basalt with thermoset and thermoplastic fabrics in FRCM specimens improves the average flexural load and flexural strength by 38% and 48%, respectively, compared to the parent basalt fabric. Similarly, there's a significant increase in energy absorption when parent basalt fabric is replaced by epoxy-coated thermoset fabric composite and hybrid yarn-based thermoplastic fabric composite for FRCM reinforcement, by 172% and 561%, respectively. This aligns with the fact that thermoplastic composites have superior energy absorption capacities compared to thermoset composites. The epoxy resin coating in TS fabric-reinforced FRCM specimens and PP polymer melt impregnation in TP fabric-reinforced FRCM specimens enhance the load-bearing and load-sharing capabilities of the basalt filament bundle, allowing the fabric to sustain higher flexural loads and achieve greater deflection in FRCM specimens.

The failed FRCM specimens show that the FRCM specimen reinforced with parent basalt exhibited complete failure through fibre fracture. The hybrid yarn-based TP fabric composite failed through a combination of fibre fracture and fibre pull-out, with fabric bridging preventing catastrophic failure (complete separation). The TS fabric composite FRCM specimen did not undergo complete fabric rupture, maintaining strong bonding with the mortar matrix, suggesting its true potential may be greater than reported. Images reveal an increase in fine microcracks, improved crack distribution, and reduced crack spacing when the parent basalt fabric is replaced by epoxy-coated TS and hybrid yarn-based TP fabric composites for FRCM reinforcement.

5.8.3 Effect of number of layer reinforcement on flexural behaviour of FRCM specimens

The flexural behaviour of various specimens – unreinforced plain mortar (PC), PP fibre-reinforced mortar (PP-FRC) without fabric reinforcement, and FRCM specimens reinforced with basalt hybrid yarn-based thermoplastic fabric composites – shows a significant improvement in flexural load and flexural strength when unreinforced mortar is replaced by PP-FRC by 123%. Further enhancements are observed as the number of fabric layers increases: 297% for 2 layers, 490% for 4 layers, and 693% for 6 layers.

Replacing PC with PP-FRC significantly increases energy absorption, with even greater improvements seen with more fabric layers. Flexural energy absorption of PC increased by 222% with the PP-FRC specimen, by 2986% with two layers of basalt TP fabric composite reinforcement, by 5980% with four layers, and by 15380% with six layers. As the number of layers in FRCM specimens increases from two to six, the reinforcement ratio (fibre volume fraction) also increases, enhancing the flexural load-bearing capacity of TRC specimens. This improvement allows them to resist higher forces before failure. Additionally, the increased number of fabric layers contributes to better deflection-hardening behaviour, improved ductility (mid-span deflection), and greater energy absorption, making the specimens more resilient under flexural loading.Fabrics made from high-performance fibres, combined with PP fibres added as secondary reinforcement in mortar mixing, synergistically improve load-bearing capacity, energy absorption, and ductility.

Failed FRCM specimens show that unreinforced PC and PP-FRC specimens exhibited failure with a single major crack leading to complete separation, although PP-FRC showed some resistance with fibre pull-out behaviour. All FRCM specimens reinforced with fabric (B-PP-1_PET_TP-F) failed through a combination of fibre fracture (fabric rupture) and fibre pull-out, with multiple fine cracks along the width. Increasing the number of fabric layers in the FRCM specimens led to more fine cracks, better crack distribution, and reduced crack spacing. The FRCM specimen with 2 layers showed complete separation, but with 4 and 6 layers, the fabric bridging effect prevented localized catastrophic failure (complete separation), thereby enhancing the effectiveness of the FRCM specimens.

5.8.4 Effect of mesh size opening of fabric on flexural behaviour of FRCM specimens

The flexural behaviour of basalt hybrid yarn-based TP fabric composite-reinforced FRCM specimens shows that as the mesh opening size decreases from 10 mm x 12 mm to 6 mm x 7 mm, the average flexural peak load and flexural strength exhibit a 31% improvement, while energy absorption increases by 72%. This improvement is attributed to the increased number of warp and weft yarns in the fabric, while maintaining the same dimensions of the FRCM specimen. Specifically, the fabric with a 10 mm x 12 mm mesh had six load-bearing warp yarns, whereas the 6 mm x 7 mm mesh had ten yarns. Images of failed FRCM specimens after flexural testing suggest that both specimens failed through a combination of fibre fracture and fibre pull-out, with fabric bridging preventing localized catastrophic failure (complete separation) and multiple fine microcracks running along the width of the specimen.

5.9 Scope for Future work

- This study focused on comparing the mechanical performance of hybrid and non-hybrid yarn-based FRCM specimens. Future research could explore the durability, thermal performance, and fire resistance of these materials.
- In this study, DREF spinning, braiding, and cabling methods were used to produce hybrid yarn. Investigating other hybrid yarn manufacturing methods and their suitability for FRCM specimens would be valuable.
- Further research could investigate the mechanical performance of FRCM specimens using other thermoplastic fibres such as PLA, PE, and Nylon in hybrid yarn structures.
- Additionally, developing and analysing numerical models based on hybrid and non-hybrid yarn-based FRCM could provide deeper insights into their performance.